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A ROBUST TEST OF EVOLUTION NEAR THE TIP OF THE RED GIANT BRANCH AND MISSING GIANTS IN NGC 2808*

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ABSTRACT

We describe a new method for robustly testing theoretical predictions of red giant evolution near the tip of the giant branch. When theoretical cumulative luminosity functions are shifted to align the tip in I-band and normalized at a luminosity level slightly brighter than the red giant bump, virtually all dependence on age and composition (heavy elements and helium abundance) is eliminated. While significant comparisons with observations require large samples of giant stars, such samples are available for some of the most massive Milky Way globular clusters. We present comparisons with the clusters NGC 2808 and M5, and find that NGC 2808 has a deficiency of bright giants (with a probability of less than about 3% that a more extreme distribution of giant stars would have happened by chance). We discuss the possibilities that underestimated neutrino losses or strong mass loss could be responsible for the deficit of giants. While we cannot rule out the neutrino hypothesis, it cannot explain the apparent agreement between the M5 observations and models. On the other hand, strong mass loss provides a potential link between the giant star observations and NGC 2808's unusually blue horizontal branch. If the mass loss hypothesis is true, there is likely a significant population of He white dwarfs that could be uncovered with slightly deeper UV observations of the cluster.

Subject headings: neutrinos — stars: evolution — stars: luminosity function — stars: mass loss — globular clusters: individual (NGC 2808, M5)

1. INTRODUCTION

At one level, our understanding of the late stages of the evolution of a low-mass giant are solid: increasing electron degeneracy in the core coupled with increasing temperature results in the "flash" ignition of helium, terminating the red giant branch (RGB). However, some of the physics inputs to the models retain some significant uncertainties (Bjork & Chaboyer 2006; Salaris et al. 2002). These uncertainties (such as electron conduction, neutrino emission, and mass loss) have significant effects on the observable characteristics of the brightest stars in old stellar populations, with corresponding influences on population synthesis models. Testing stellar models for the late RGB is difficult though because the stars evolve on short timescales make up a small fraction of all of the stars in a population.

Because NGC 2808 is a very massive globular cluster ($M_V = -9.39$; Harris 1996) and because the stars within it appear to have nearly uniform metal content, it provides us with one of the largest "clean" samples of stars for examining the late phases in stellar evolution. At the same time, NGC 2808 has an extremely peculiar bimodal distribution of horizontal branch (HB) stars that has been known since the first moderately-deep photometry was taken (Harris 1974). The first deep color-magnitude diagram (Sosin et al. 1997) was an even greater shock, revealing a blue HB tail extending 3.5 mag fainter in V and containing two additional gaps in the distribution of stars. As such, NGC 2808 is one of the more obnoxious examples of the "second parameter" problem, in which HB star distributions cannot be explained based on metallicity alone. While some aspects of the HB distribution have been explained since the original observations, the overall bimodality and extended blue HB tail have not. The most recent photometric study of the cluster by Castellani et al. (2006) used archival *Hubble Space Telescope (HST)* images along with wide-field ground-based observations. Their sample can be improved upon, however, because they only used a fraction of the HST observations available.

2. OBSERVATIONS AND DATA REDUCTION

Three *HST* datasets were used in this work. The only dataset that had not been previously published was obtained with the HRC detector of the Advanced Camera for Surveys (ACS) using $F435W$ and $F555W$ filters as part of proposal ID 10335 (P.I. H. Ford). We also reduced archival WFPC2 images from proposals 6095 and 6804 (PIs Djorgovski and Fusi Pecci). The HRC images mostly overlap the fields of the PC chips, but allowed us to resolve a number of stars that were blended in the WFPC2 images.

The HRC frames were processed using the DOLPHOT photometry package [1] with its module tuned for ACS data. Individual frames (prior to drizzling in the ACS

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[1] http://purcell.as.arizona.edu/∼andy/dolphot/

pipeline) were obtained from the ACS team in order to get photometry on the giant stars. For the photometry, differences in effective pixel area were corrected within DOLPHOT through the use of a pixel area map provided on the ACS website [2]. For *relative* astrometry, we used the fourth-order polynomial corrections provided in the most recent IDCTAB file for the dataset (q692007bj_idc.fits) to facilitate the creation of a common coordinate system with the WFPC2 images. The WFPC2 images were analyzed using the HSTPhot photometry package [3]. Images from proposal 6095 were taken in the $F218W$, $F439W$, and $F555W$ filters, while those from the proposal 6804 were taken in the $F160BW$, $F336W$, $F555W$, and $F814W$ filters. $F439W$ and $F336W$ observations were particularly useful for separating AGB stars from the RGB. Known geometric distortions in WFPC2 images were corrected using the METRIC task in the STSDAS package within IRAF.

Of the filters available, $F814W$ is most appropriate for giant branch study since near-infrared filters are most directly correlated with luminosity. To maximize the size of our sample we used common stars from the two WFPC2 fields to derive a transformation from the $(m_{439}-m_{555}, m_{555})$ color-magnitude diagram to m_{814} using a second-order polynomial containing magnitude and color terms. The residuals show no systematic trends with magnitude or color over the range considered. The median residual was -0.001 mag for the 814 stars in common, with a semi-interquartile range (half of the difference between the 25th and 75th percentile in the ordered list of residuals) of 0.030 mag.

3. ANALYSIS

The very tip in I has been used as a distance indicator for large, old stellar populations largely thanks to its very weak dependence on age and chemical composition (see Da Costa & Armandroff 1990 for an early reference). This can be seen empirically in CMDs of composite stellar populations in nearby galaxies (for recent examples, see Rizzi et al. 2006; Mouhcine et al. 2005; Bellazzini et al. 2005). Theoretical predictions confirm that the composition dependence is very weak for [Fe/H] $\lesssim -1$ (VandenBerg et al. 2006).

Even with the large number of RGB stars in NGC 2808, it is worthwhile to find the most robust comparison with models possible. The tests below involve cumulative luminosity functions (LFs), counting stars starting at the observed TRGB. A comparison with models requires a magnitude shift (akin to the distance modulus) and a vertical normalization. For the horizontal (magnitude) shift, we have opted to shift the models to the observed magnitude of the brightest cluster giant. As noted above, this has the advantage that it is largely independent of chemical composition and age (although its absolute position is affected by uncertainties in physics that affect the timing of the helium flash). For the vertical normalization, we have forced the models to have a number of stars equal to the number of observed stars just brighter than the RGB bump at $m_{814} = 14.8$. As seen in Fig. 1, by normalizing in this way, the models for a wide range of compositions (heavy elements and helium) and ages overlie each other to a high degree. To state this another way, the late evolution of RGB stars is virtually independent of input parameters, and results from the strong correlation between luminosity and mass of the helium core.

While there is little dependence on age or composition, there are differences in physics from model set to model set that affect the cumulative LF. In the bottom right panel of Fig. 1, we compare the predictions from models by the Yale-Yonsei (Demarque et al. 2004), Teramo (Cassisi et al. 2004), and Victoria-Regina (VandenBerg et al. 2006) models. The Teramo and Victoria-Regina predictions overlie each other almost perfectly, while the Yale-Yonsei models predict considerably more giants (and therefore slower evolution) near the TRGB. The two Yale-Yonsei models use different bolometric corrections. While this does affect the cumulative LF, it does not account for the entire difference with the Victoria-Regina and Teramo models. The implementation of neutrino energy loss rates is probably responsible for the difference: the Yale-Yonsei models employ Itoh et al. (1989) rates, while the Teramo models use (Haft et al. 1994) rates and the Victoria-Regina models use Itoh et al. (1996) rates. The dominant plasma neutrino emission rates have been updated several times since the Itoh et al. (1989) paper, and the values used in the Yale-Yonsei isochrones are probably too low, which allows giants to evolve more slowly because nuclear reactions don't need to provide for larger neutrino energy losses. As corroboration, we note that the Yale-Yonsei models have lower luminosities at the TRGB ($\log(L/L_\odot) \approx 3.33$) than the Teramo and Victoria-Regina models ($\log(L/L_\odot) \approx 3.37$), consistent with lower cooling rates and an earlier flash. This is an important issue because systematic uncertainties in the characteristics of the helium flash translate to corresponding uncertainties in the properties of HB stars, including their luminosities.

In Fig. 2, we compare the observations for NGC 2808 and for M5 (Sandquist & Bolte 2004) to the Victoria-Regina models (though the results are nearly the same for the Teramo models). To judge the significance of the differences, we used two methods to estimate the probability of detecting a *smaller* sample of bright giants if they were drawn from a cumulative distribution given by the Victoria-Regina models — these are essentially estimates of the probability of a "false alarm". First, we did one-sided Kolmogorov-Smirnov (K-S) tests at various brightness levels. This was necessary because adjustment of the faint limit for the giant sample affects the size of an absolute deviation in the cumulative distributions (the statistical quantity used in the test) as well as the total sample size, both of which affect the computed significance of a deviation. When the faint limit is set 1.8 magnitudes below the TRGB, the RGB sample is 142 stars for NGC 2808, the maximum absolute deviation is 0.11, and the probability that a sample of the same size with a more extreme deviation would be drawn from the theoretical distribution is 4.3%. By comparison, for M5 the sample was 91 stars, the maximum absolute deviation was 0.06, and the probability was 89% that a sample with a more extreme deviation would be drawn from the theoretical distribution. By comparison, there is a 0.9% chance that a distribution drawn from the

[2] http://www.stsci.edu/hst/acs/analysis/PAMS
[3] http://purcell.as.arizona.edu/∼andy/hstphot/

Yale-Yonsei model would deviate to a larger degree than the observed NGC 2808 distribution, and a 28% chance that one would deviate more than the M5 distribution.

Our second method used predictions from a binomial distribution function. Salaris & Cassisi (1997) used a similar formulation to determine the likelihood of finding stars within a certain magnitude range near the TRGB. If we have a total sample of RGB stars N_{RGB} brighter than a certain level, then the theoretical cumulative luminosity function can be used to predict the probability P_i that any one star in that sample will be found in the brighter portion of the sample (brighter than a second faint limit that is closer to the TRGB). If the theoretical cumulative luminosity function provides an accurate model of the relative evolutionary timescales for the giants, then the probability of measuring a number of stars $n \leq N$ in the brighter portion of the sample is

$$P_{\leq N} = \sum_{n=1}^{N} \frac{N_{RGB}!}{n!(N_{RGB}-n)!} P_i^n (1-P_i)^{(N_{RGB}-n)}.$$

For NGC 2808, we used the RGB sample between the TRGB and $m_{814} = 14.8$ just brighter than the RGB bump ($N_{RGB} = 441$). We find that the probability reaches a minimum of about 1.3% for a faint limit of $m_{814} = 12.4$ ($N = 36$ and $P_i = 0.115$), but is less than about 5% for $m_{814} \leq 12.5$ ($N = 46$). Both of our methods agree that the probability of a false alarm for NGC 2808 is (conservatively) less than 5%.

The horizontal (magnitude) shift used to align the model and observed TRGB has a small effect on the calculated probabilities. Because we use the brightest *observed* giant, we underestimate the luminosity of the TRGB by some amount. However, because the models appear to be overestimating the number of bright giants, this only ends up making our test probabilities conservative overestimates. The probability of finding at least one star within a certain magnitude of the TRGB can be determined from the binomial distribution and an assumed cumulative luminosity function (Salaris & Cassisi 1997). Using the Victoria-Regina models, we find there would be a 50% probability of having at least one star within 0.02 mag of the TRGB for a sample of the same size as the one in NGC 2808. If the brightest NGC 2808 giant is as much as 0.05 mag fainter than the TRGB (the binomial distribution predicts less than a 5% chance of this), the K-S probability would be reduced to 2.6%. The probabilities derived from the binomial distribution increase slightly if the TRGB brightness is underestimated: a 0.05 mag underestimate increases the minimum probability from 1.3% to 2.1%. Thus, the deficit of bright RGB stars in NGC 2808 seems secure.

We have two possible explanations for the observations. First, larger neutrino emission rates would accelerate evolution near the TRGB, as mentioned above with regard to the Yale-Yonsei models. The NGC 2808 observations may be showing this clearly, while statistical fluctuations may be concealing it in M5. We have no reason to believe that RGB neutrino emissions should differ systematically from cluster to cluster, so this explanation would disconnect the deficit of RGB stars from discussions of HB morphology. The I-band location of the discrepancy in the NGC 2808 CLF (starting ~ 1.6 mag below the TRGB) holds some physical information if it results from greater-than-predicted cooling of giant cores. As long as the temperature and density sensitivities of the plasma neutrino emission rates agree with those of Haft et al. (1994), modifications of the emission rate are unlikely to explain the NGC 2808 observations because they would primarily affect RGB stars within about 1 mag of the TRGB. For typical RGB core conditions, the energy loss rate has fairly large temperature and density dependences ($q \propto \rho^{2.5} T^9$, evaluated from the Haft et al. 1994 formulae) that are responsible for a rapid increase in energy loss. Of course, if there is an energy loss mechanism having different density and temperature dependences, then the shape of the LF would be changed. While we cannot rule out the possibility of systematic errors in the theoretical neutrino loss rates used in the stellar models, new physics would probably be required to match the observations.

A second explanation involves enhanced mass loss near the TRGB for a *fraction* of the stars. Models predict that stars can leave the RGB before He flash if the mass of the star's envelope decreases below a critical value. These stars can have a "hot flash" He ignition after leaving the RGB, before finally appearing on the blue end of the HB for a time approximately as long as that of a typical HB star. With even more mass loss on the RGB, a star will leave the RGB earlier, a hot He flash will be prevented, and a He white dwarf would result. According to models (D'Cruz et al. 1996), stars leaving the RGB before they get within 0.4 mag of the TRGB will produce He white dwarfs. In NGC 2808, the vast majority of the stars seen on the HB in NGC 2808 should have gone through the entire RGB phase (complete with He flash) because their positions on the HB imply substantial envelope mass. However, the deficit of stars more than 0.4 mag fainter than the TRGB would imply we should expect to have a significant population of He core white dwarfs if the mass loss hypothesis is true. Based on the lack of a blue HB tail in M5, we would not expect an RGB deficit there.

The population ratio $R = N_{HB}/N_{RGB} = 1.62 \pm 0.07$ (Castellani et al. 2006) is near the average for Galactic globular clusters (Salaris et al. 2004). However, this ratio could retain a "normal" value if giants are removed exclusively from the upper RGB (which is the most sparsely populated), or if the stars avoiding the HB phase (by never igniting He) are small in number. If there is a large population of He white dwarfs, they may be detectable at the bright end of the white dwarf cooling sequence because they cool more slowly than the CO white dwarfs produced by traditional evolutionary paths (Castellani et al. 2006). Dieball et al. (2005) identified about 40 white dwarf candidates using STIS UV imagery, and found the numbers to be in rough agreement with theoretical predictions. Unfortunately, the Dieball et al. survey does not reach far down the WD sequence, and models (Serenelli et al. 2002) predict that the cooling age of a He WD is only about twice the cooling age of a CO WD near their completeness limit. (The ratio becomes much more extreme the fainter one goes.) Thus, if the He WD population is less than the size of the observed population, the production rate for He WD must be less than about half the CO WD production rate.

If the true luminosity function of RGB stars is given by the Victoria-Regina or Teramo models, then NGC 2808 shows a deficit in $\log N$ of at most about 0.1 (20% in

N) in the magnitude range where He WDs are probably produced ($I - I_{TRGB} \gtrsim 0.4$). If these "missing" giants produce He WDs directly, then this would enhance the observable population of WDs in the Dieball et al. sample by about 40%. The uncertainties in the theoretical predictions and in the WD numbers are not yet able to rule this possibility out. A slightly deeper survey of the cluster's WD population would help definitively settle whether there is a significant population of He WDs. Such a survey has been done for ω Cen (Monelli et al. 2005), another cluster with a extensive blue HB tail, and again the results are in rough agreement with evolutionary timescales. However, Monelli et al. also note that the observed WDs appear to be redder than expected, and one of the possible explanations of this is a large population of He core WDs.

4. DISCUSSION

Because our analysis implies that the RGB evolution is virtually independent of chemical composition and age inputs, it should be possible to merge photometric data for stars from clusters with relatively heterogeneous characteristics. Multiple cluster samples could place *very* tight constraints on physics inputs like neutrino losses (and non-standard neutrino emission mechanisms as well). Indeed, our comparisons indicate that the neutrino losses used by the Yale-Yonsei models can already be ruled out based on the comparisons with the massive globular clusters M5 and NGC 2808.

Although our method can only be applied in a practical way to the most massive globular clusters, it does provide a new way of probing the "second parameter" problem in horizontal branch stars. If there is a dynamical influence on cluster giants causing them to leave the RGB early in NGC 2808, then we would expect similar features to be present in other clusters with extreme blue HB tails. Alternately, for a cluster like 47 Tuc with no obvious blue HB extension, the upper RGB should match models.

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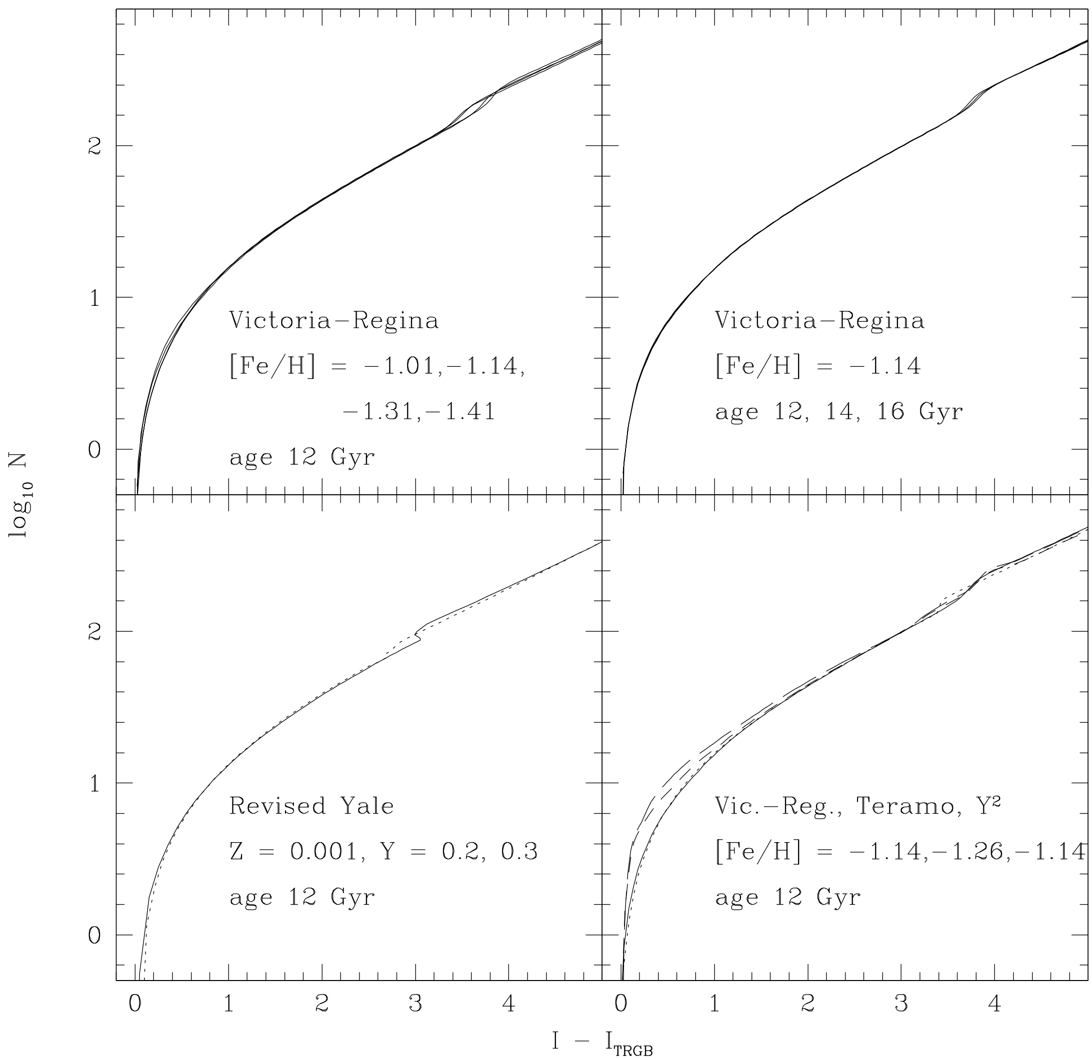

FIG. 1.— Comparisons of theoretical cumulative luminosity functions after shifting in magnitude to match the tip of the RGB in I band, and normalizing just above the RGB bump. The models are Victoria-Regina (VandenBerg et al. 2006), Teramo (Cassisi et al. 2004), Yale-Yonsei (Demarque et al. 2004), and Revised Yale (Green et al. 1987) isochrones. In the lower right panel, the Victoria-Regina and Teramo models overlap. The two Yale-Yonsei models with T_{eff}-color transformations from Green et al. 1987 (*short dashed line*) and Lejeune et al. 1998 (*long dashed line*) fall higher.

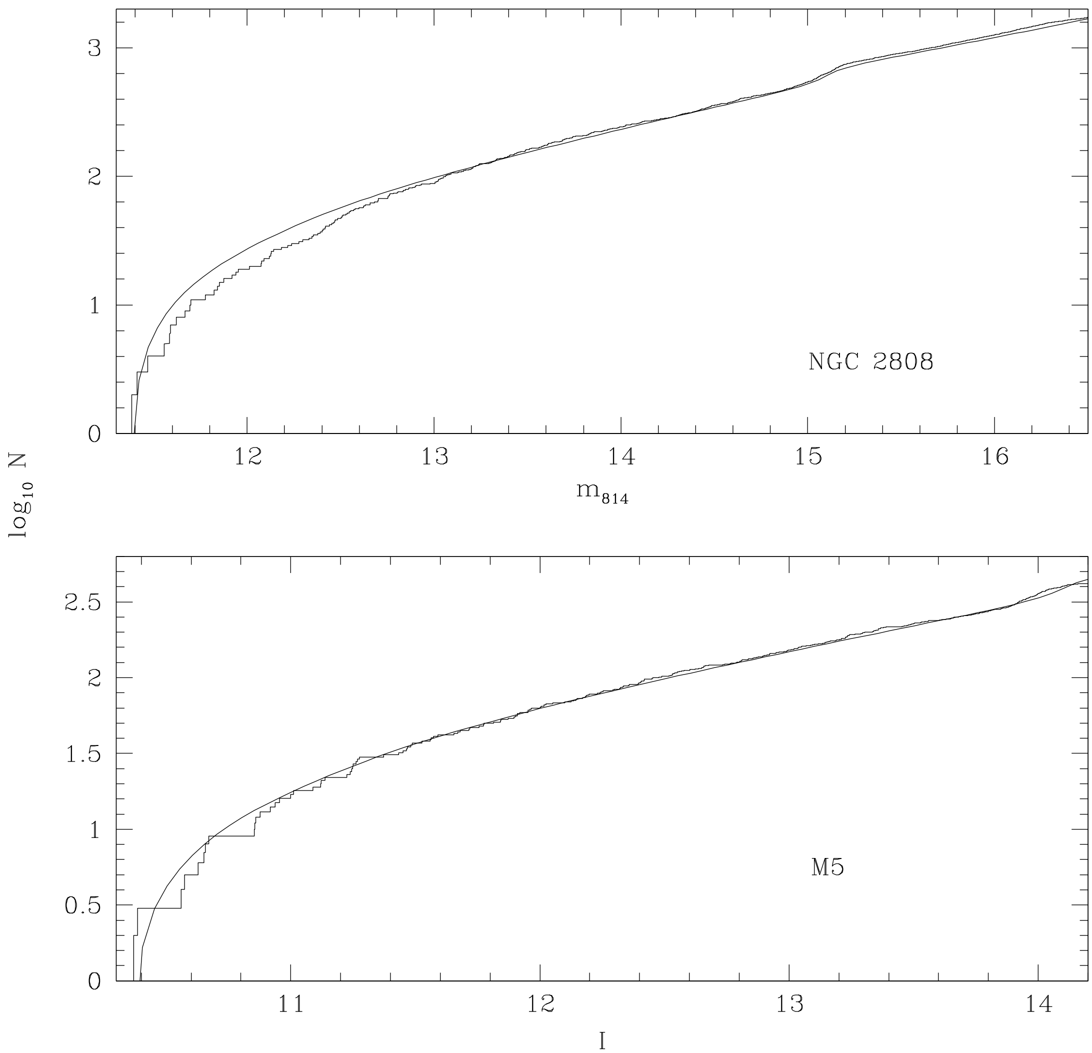

Fig. 2.— The cumulative luminosity function for bright RGB stars for NGC 2808 (this work) and M5 (Sandquist & Bolte 2004), along with a Victoria-Regina model (VandenBerg et al. 2006) for [Fe/H] = -1.14 and age 12 Gyr.